

Structural modeling and design of tall buildings composed of ultra-lightweight floor systems

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ABSTRACT

The main objective of this paper is to investigate rigidity and to develop structural modeling and design concepts of ultra-lightweight (ULW) floor composite used in combination with steel frame of tall buildings. The main vehicle in this study was structural modeling and analysis of six and twenty-four story buildings in which their floor systems were modeled using reinforced concrete (RC) and ULW slabs with flexible and rigid behaviors. For both RC and ULW cases, the flexible diaphragm action was incorporated in the model by assigning the respected actual in-plane mechanical properties; while the rigid action was modeled by assuming that the floor masses were lumped at the center of mass with constrained out-of-plane floor deformation. The focus of the analysis is on comparing the key structural performances between those two cases including lateral deflection (drift), structural period, base shear, and floor rigidity (flexibility). The primary loads considered were dead load, live load, lateral loads (wind and earthquake), and their load combinations. The ULW slab was made of high strength cross laminated timber (CLT), one of the high end timber-based composite products that have been used widely in Europe for low-rise building applications. In combination with steel and/or reinforced concrete frames, CLT has potential application to be used in a very demanding tall building industry in the middle-east due to its strength, lightness, low demand on foundation, architecturally appealing, and environmentally friendly. The outcome of this study is intended to assist structural engineers in designing and analyzing composite or hybrid floor utilizing this type of ULW material, particularly in dealing with whether to consider actual or assumed rigid behavior of the floor system.

Keywords: Lightweight floor, cross laminated timber, hybrid tall buildings, structural modeling, lateral drifts, dynamic performance.

1. INTRODUCTION

Floor selection in tall building design is one of the important decision structural engineers have to make, since it composes of around 20% of the total structural weight. Lateral load generated from wind or earthquake is transferred to the lateral load resisting system according to respected lateral stiffness at each floor level. The

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traditional way in designing floor system of tall buildings is to apply composite action between reinforced concrete (RC) slab and steel frame that supports it (Fig. 1a). The shear connectors that connect RC and steel frame are normally designed to achieve this composite action with no slip assumed between the slab and steel frames. The RC slab thickness can be designed in the range of 100-160 mm depending on whether the concrete is cast in place (via corrugated steel deck) or precast (via preassembled connections). For non-traditional floor system with ultra-lightweight (ULW) materials such as cross laminated timber (CLT), connections between the slab and steel frame is important to achieve intended rigidity or flexibility of the diaphragm (Fig 1b). Partial composite action is normally considered in the design due to flexible mechanical connectors that leads to slip between the slab and steel frame. CLT thickness ranging from 150 to 300 mm can be designed for this type of floor system.

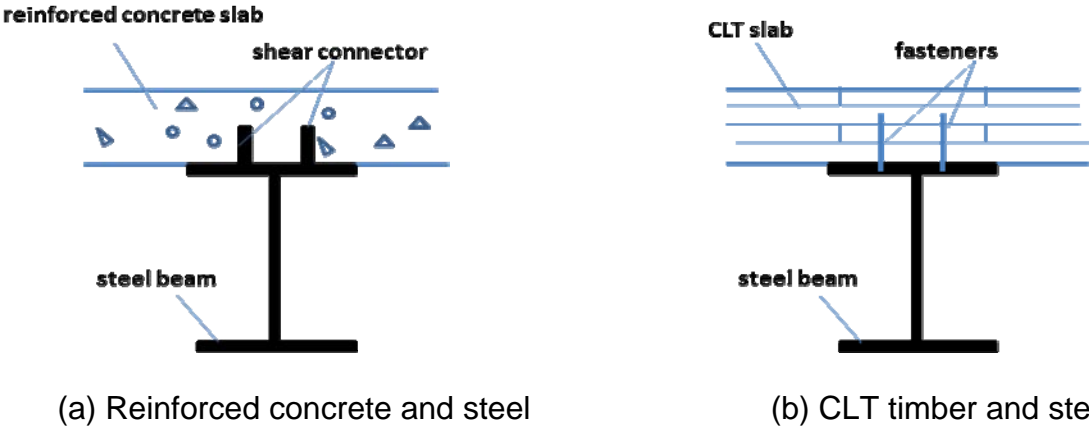


Fig. 1 Floor system of multi-storey buildings

Previous studies indicate that it is feasible to replace traditional RC slab with CLT (Asiz and Smith, 2009; Asiz and Smith, 2011). CLT is one of the high ends of timber-based composite products that have been used widely in Europe for low-rise building applications. Recently it has become a trend in Europe and North America to utilize it in higher building application in combination with other common structural materials such as concrete and steel (Gagnon and Pirvu, 2011). Using case studies of multi-storey building with steel main skeletons, it was shown that the demand for the steel materials of the buildings are much reduced using CLT slab relative to RC slab without sacrificing the important structural performance such as lateral deflection (drift) due to external lateral loads. Also, the reaction loads imposed to the structural supports are significantly reduced due to much lighter CLT slab used without compromising its strength. This is due to the fact that CLT has mass about one-third to one-half of the RC slab resulting in lower inertial response generated from earthquake load. Concerns regarding the use of timber-based products in floor of tall building such as fire and sound performance can be minimized by adding fire resistant material layers to the floor and by designing sound absorbent materials in between the junction and connection between steel and slab (Weckendorf and Smith, 2012).

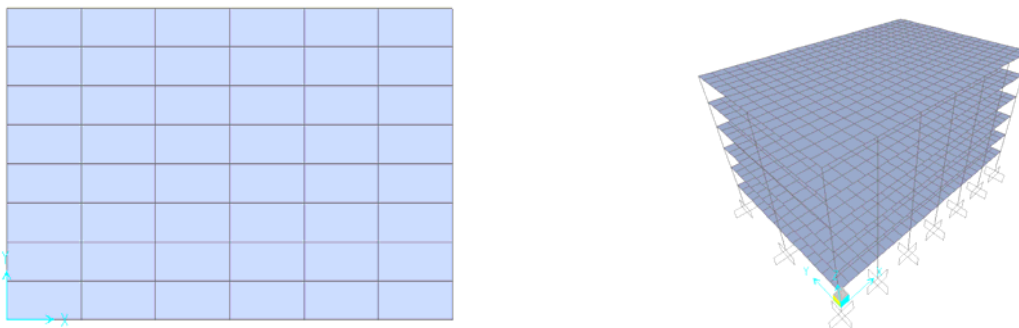
Previous studies incorporated full consideration of the actual properties of both RC and CLT slabs used in the structural modeling. This could impact in the design and

modeling complexity faced by day-to-day structural engineers, because it requires big effort in allocating number of detailed structural elements (e.g. link/connectors, floor shell elements) to model flexible (or actual) behavior of the floor diaphragm. This study will investigate whether rigidity (or flexibility) has significant impact on the structural performance of steel framed buildings with ULW floor considering also reference case of conventional RC floors.

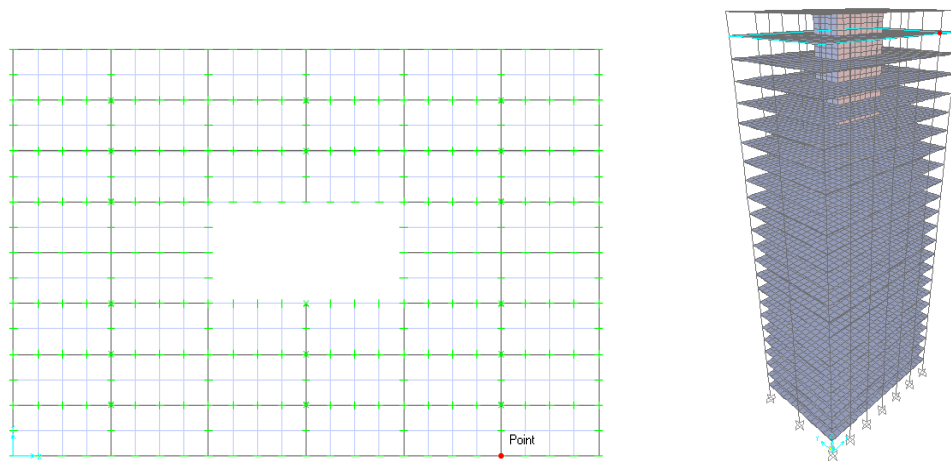
2. METHODOLOGY

Case studies using six and 24-storey buildings will be numerically modeled (Fig 2). Two major models will be incorporated in the floor modeling utilizing RC and CLT slabs: rigid and flexible diaphragms. For the six-storey building which will be representing low-rise building with simple floor layout, the lateral load resisting system was carried by moment connection in the steel frame. For the 24-storey case representing tall building with complex floor layout, the lateral load resisting systems consisted of RC shear wall cores in combination with moment resisting frame (RC or steel framework). Major load considered was wind and earthquake. Loads combinations considered included effects of gravity (self-weight and imposed floor and roof loads), seismic load with peak design acceleration 0.5g, and wind forces with basic wind speed 240 kmh. Details of the loads data and load combination factors are given in Asiz and Smith (2009a). These extreme loads combination would actually never be done in the actual design practice. Nevertheless, it is important design information considering hypothetically building located in the extreme zone with respect to earthquake or wind load.

Fully 3-D finite element models with SAP2000 were used to predict structural responses under these loads, Fig 2 (CSI, 2013). For representing flexible diaphragm, the floor and roof components were modelled as four node shell elements having six degree of freedoms – three translations and three rotations. Linear dynamic analysis via response spectrum method was used to apply seismic load at the building base without making presumption about lateral load distribution to the diaphragms such as is done via equivalent static lateral force method. Table 1 summarizes material properties used in the flexible floor analysis. For the rigid diaphragm modeling, the floors were modeled by assuming that their masses were lumped at the center of floor mass with constrained out-of-plane floor deformations. Detail modeling justifications can be seen in Asiz and Smith (2009).



(a) 6-storey building with 4-m-height at each level (typical floor layout 19.2 m x 12.8 m)



(b) 24-storey building with 4-m-height for each level (typical floor layout 38.4mx25.6 m)

Fig. 2 Three-dimensional structural modeling of the buildings studied

Table 1: Material properties used in the analysis

	Steel	Concrete	CLT
Directional property	isotropic	isotropic	orthotropic
Density (kg/m ³)	7200	2400	400
Elastic modulus (GPa)	200	25	E ₁ =9 E ₂ =4.5 G ₁₂ =0.5
Poisson's ratio	0.30	0.25	v ₁₂ =0.3
Strength (MPa)	250	27.5	f _{t-1} =20, f _{t-2} =15 f _{c-1} =30, f _{c-2} =25 f _{shear} =5
Notation: E = modulus of elasticity; G = modulus of rigidity; 1 = CLT major direction; 2 = CLT minor direction; t = tension; c = compression			

3. RESULTS

Fig 3 shows the lateral deformation (drift) for both six-storey and 24-storey buildings using RC and CLT slabs. As was anticipated, the critical lateral load for the RC and CLT floor systems was due to combination of gravity and earthquake loads. The drifts and inter-storey drifts obtained in this study were less than the allowable drift stated in the building code (e.g. NRC 2005, ICC 1997). In general, it can be seen that for both six and 24-storey cases, CLT floor system has much lower drift relative to RC system. For the six-storey case (flexible floor), the predicted drift at the roof level for the RC system is 83 mm and 62 mm (25 % less) for the CLT system. For the 24-storey case (flexible floor), the predicted maximum drift of the RC system at the roof level is 180 mm, and 130 mm or 27% less for the CLT system. Overall, the results showed that

CLT systems have much reduced drift relative to RC systems. This is a direct reflection of the mass of the CLT system slabs being only about half of the mass of equivalent RC system slabs.

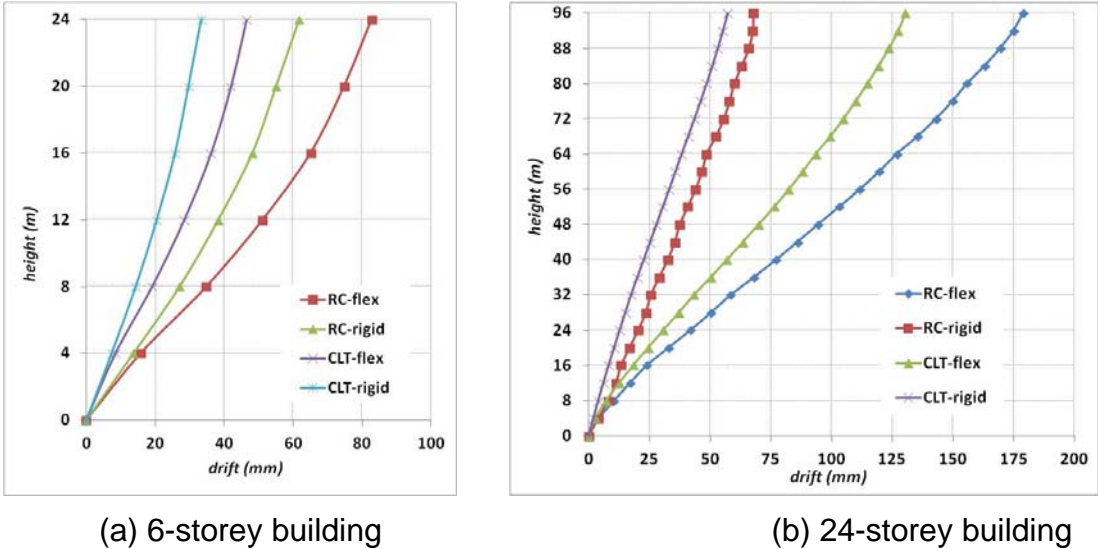


Fig. 3 Drift comparison

For the rigidity (or flexibility) analysis, ratio of the drift between flexible and rigid floors was compared. For the six-storey case, the ratio found in CLT system was 1.15 (first storey) to 1.39 (sixth storey) where the latter value indicates the highest storey ratio. As expected, the ratio is getting bigger when the storey gets higher. While the ratio in RC system is 1.15 to 1.34 slightly lower than that of CLT's. For the 24-storey case, the ratio in CLT system is 1.37 to 2.28, and in RC system 1.07 to 2.65. Regardless of the floor materials used, the ratio in the 24th level is highest indicating that the error obtained is biggest. This is because in the 24-storey case, the floor layout is much more complex compared to the 6-storey layout. Also, this indicates that the vertical stiffness of the lateral load resisting system that is carried by the RC shear wall is much higher than the horizontal stiffness of the floor system. By comparing the flexibility of the floor material used, as anticipated, RC system showed higher lateral stiffness particularly for the 24-storey case. The results obtained in this study are pretty much consistent with those obtained in the previous study (e.g. Ju and Lin, 1999).

Trends were also observed when analogous ratios are applied to fundamental structural period and maximum base shear, as shown in Tables 2 and 3 below. Based on the case study results, it can be concluded that it is necessary to model floor as flexible regardless of the floor materials used particularly for the case of irregular floor layout, i.e. floor that has lower horizontal stiffness compared to the lateral stiffness of the lateral load resisting system.

Table 2: Fundamental period (seconds)

	6-storey		24-storey	
	RC	CLT	RC	CLT
Flexible	1.23	0.73	2.91	1.98
Rigid	0.97	0.52	1.41	0.74

Table 3: Maximum base shear (kN)

	6-storey		24-storey	
	RC	CLT	RC	CLT
Flexible	3,558	2,082	10,276	7,129
Rigid	4,031	2,521	17,461	14,602

Notes:

- 6-storey: Total weight with RC=24,330 kN and Total weight with CLT=8,132 kN
- 24-storey: Total weight with RC=118,263 kN and Total weight with CLT=58,320 kN

4. DISCUSSION

For the 24-storey case, since the building is slightly unsymmetrical about the X-axis, a combination of earthquake load in the two orthogonal directions using 100%-X and 30%-Y would produce torsional (unsymmetrical) response causing the diaphragm to deform as a deep beam in flexure (Fig 4). As was anticipated, the critical in plane deformation occurred at the 23rd storey due to higher drifts generated at the diaphragm with cores opening. The deformed shape of the diaphragm in the 23rd storey with the steel framework system indicates that CLT has flexibility around 2.5 and the RC has a slightly lower value of 2.3. [Note: The flexibility ratio here is defined as the ratio between the average lateral drift at the floor diaphragm and the drift at the mid-span floor diaphragm (ASEC, 2005)]. While for the RC framework, CLT has flexibility around 2.7 and the RC 2.4. However, this should not be a big issue in practice, since highly deformed (flexible) diaphragms are accommodated through designing adequate frames (chords) at the building perimeter to resist the flexural action and enough collector frames capable of transmitting lateral forces to the vertical lateral-force-resisting systems. The other earthquake loading direction (30%-X+100%-Y) that resulted in critical drifts produced diaphragm flexibilities (for both systems) in the order or 1.1, which is quite rigid.

For the six-storey case, no significant different in the rigidity was obtained between RC and CLT systems. Rigid floor assumption is reasonable for floor simple layout and without shear wall core.

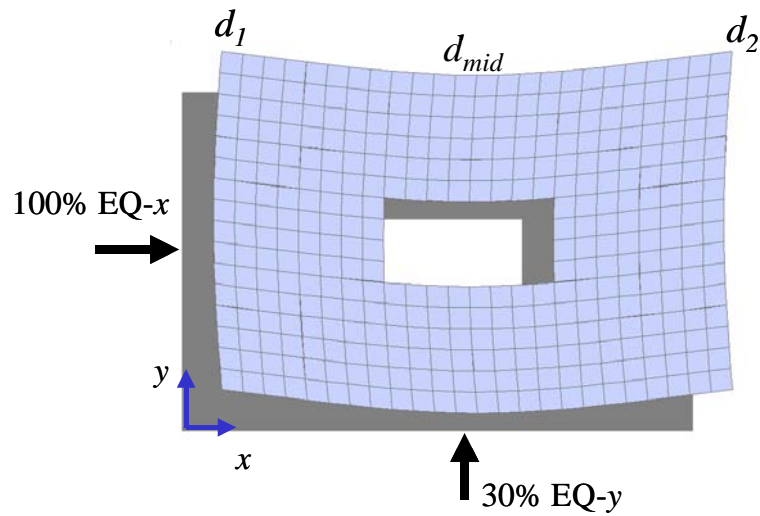


Fig. 4 Flexibility analysis

For the CLT floor, the connection between the slab and steel frame can be modeled as rigid, provided in the design that the mechanical connectors (e.g. long screws) are designed based on the force demand. Extended modeling work results indicated that there was no big discrepancy in the structural performances (less than 5%) between the floor systems in which their connection systems were modeled using actual connector stiffness and using rigid connectors. This would actually save modeling effort as in the general RC floor design and analysis.

5. CONCLUDING REMARKS

The result indicated that significant differences in the structural performances were found between flexible (actual properties) and rigid floor models for tall building with complex floor layout and shear wall core. The CLT system shows larger differences relative to the RC system due to difference in the lateral stiffnesses between CLT slab and RC shear wall cores. The rigid versus flexible assumptions would yield close results in the overall structural response for a case when there is no RC shear wall and only moment frame that resists the lateral load.

So far the analyses were performed without inclusion of P-delta (secondary) effects. However, this would not alter the merits of using CLT slabs relative to the RC slabs because force amplifications due to secondary effects will still favour the lightness of CLT.

Other case studies incorporating complex floor layout and building irregularities are under way. The design values to calibrate error due to incorporating rigid floor behavior can then comprehensively be presented.

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